

THE PHASE COHERENCE OF INTERSTELLAR DENSITY FLUCTUATIONS

BLAKESLEY BURKHART¹, A. LAZARIAN²*Draft version November 13, 2015*

ABSTRACT

Studies of MHD turbulence often investigate the Fourier power spectrum to provide information on the nature of the turbulence cascade. However, the Fourier power spectrum only contains the Fourier amplitudes and rejects all information regarding the Fourier phases. Here we investigate the utility of two statistical diagnostics for recovering information on Fourier phases in ISM density data: the averaged amplitudes of the bispectrum and the phase coherence index (PCI), a new phase technique for the ISM. We create 3D density and 2D column density maps using a set of simulations of isothermal ideal MHD turbulence with a wide range of sonic and Alfvénic Mach numbers. We find that the bispectrum averaged along different angles with respect to either the k_1 or k_2 axis is primarily sensitive to the sonic Mach number while averaging the bispectral amplitudes over different annuli is sensitive to both the sonic and Alfvénic Mach numbers. The PCI of density suggests that the most correlated phases occur in supersonic sub-Alfvénic turbulence and also near the numerical dissipation regime. This suggests that non-linear interactions with correlated phases are strongest in shock dominated regions, in agreement with findings from the solar wind. Additionally, our results are particularly encouraging as they suggest the phase information contained in the bispectrum and PCI can be used to find parameters of turbulence in column density maps.

Subject headings: ISM: structure — MHD — turbulence

1. INTRODUCTION

Magnetohydrodynamic (MHD) turbulence is ubiquitous in space plasmas across many orders of magnitude in scale. This includes the solar wind at astronomical unit scales, the interstellar medium (ISM) at parsec scales, and intercluster medium (ICM), at megaparsec scales (see for a review Elmegreen & Scalo 2004). In the solar wind, turbulence velocity and magnetic perturbations can be directly measured via in-situ spacecraft however, in the ISM and ICM turbulence must be measured indirectly through line of sight tracers such as column density and spectral lineprofiles (see Lazarian 2009).

The traditional measure of turbulence on Earth as well as in astrophysical environments is the spatial Fourier power spectrum. This is because the turbulence energy transfer cascade can be studied by examining the Fourier power spectrum and the sources and sinks of energy, including the injection and dissipation scales, can be identified. For studies of turbulence in the ISM, the power spectrum of density and velocity (and its variants such as the structure function and delta variance) has been suggested by several authors to provide information on the spatial and kinematic scaling of turbulence, sonic Mach number and injection/dissipation scales (Kowal et al. 2007; Burkhart et al. 2010; Ossenkopf 2002; Collins et al. 2012; Federrath & Klessen 2013).

The power spectrum is defined as:

$$P(\bar{k}) = \sum_{\bar{k}=const.} \tilde{F}(\bar{k}) \cdot \tilde{F}^*(\bar{k}) \quad (1)$$

where k is the wavenumber and $\tilde{F}(\bar{k})$ is the Fourier trans-

form of the field under study.

Equation 1 demonstrates a critical limitation of the Fourier power spectrum which is that it contains only the information on amplitudes and disregards all the phase information. This is problematic for studies of MHD turbulence because interactions among MHD waves can produce finite correlations of wave phases which are completely missed by the power spectrum. The coherence or randomness of phases in the MHD turbulence cascade is of critical importance for particle transport and the understanding of wave interaction. In light of this, several authors have suggested various techniques which extend beyond the power spectrum to include information on phases.

One such technique that preserves the phase information has been applied in the context of the ISM is the bispectrum. The bispectrum is closely related to the power spectrum. The Fourier transform of the second-order cumulant, i.e. the autocorrelation function, is the power spectrum while the Fourier transform of the third order cumulant is known as the bispectrum. The bispectrum contains information on both amplitudes and phases and has been applied to both MHD simulations (Burkhart et al. 2009; Cho & Lazarian 2009) and observations of neutral hydrogen (Burkhart et al. 2010). These studies found that the bispectrum is a sensitive diagnostic for the sonic and Alfvénic Mach numbers and could describe the behavior of nonlinear mode correlation across spatial scales.

Another technique, used thus far in the context of the solar wind community, to investigate phase information is the so-called phase coherence index (PCI, see Hada et al. 2003; Koga & Hada 2003; Koga et al. 2007; Chian et al. 2008; Chian et al. 2010). The PCI uses a surrogate data set in which the phase information in a particular image or signal is randomized and another in which

¹ Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 0213

² Astronomy Department, University of Wisconsin, Madison, 475 N. Charter St., WI 53711, USA

the phase information is perfectly correlated. These surrogate data share the same power spectrum with each other and the original data however have different phases. Comparison of the original data and the surrogates gives insight into the level of phase coherence or randomness. PCI has been applied to solar wind observations and simulations but until now there has not been an application to MHD turbulence in the context of the ISM or ICM.

In this paper we investigate the application of the bispectrum and PCI on MHD simulations geared towards ISM observations. In principle, the starting point for the definition of both the bispectrum and the phase coherence technique is the Fourier transform, \hat{F} . We can describe the power by computing $P(\vec{k})$ and the phase distribution $\phi(\vec{k}) = \tan^{-1}((\text{Im}(\hat{F})/\text{Re}(\hat{F}))$.

In particular we are interested in the physical processes that cause nonlinear phases to be correlated or uncorrelated, i.e. are phase techniques sensitive to the amplitude of turbulence fluctuations, the magnetic field strength or the sonic Mach number? Most importantly, we seek to understand if phase techniques could be useful for observations of ISM turbulence and focus our analysis on fluctuations in 2D column density maps. This paper is organized as follows: in Section 2 we discuss the MHD simulations used for the study of the bispectrum and PCI. In Section 3 we discuss our results of a new averaging procedure to the 2D isocontours of the bispectrum. In Section 4 we present the first application of the PCI to simulations of ISM MHD turbulence. Finally in Section 5 and 6 we discuss our results followed by our conclusions.

2. SIMULATIONS

We use the database of 3D numerical simulations of isothermal compressible (MHD) turbulence with resolution 512^3 presented in a number of past works (e.g. Kowal, Lazarian & Beresnyak 2007; Burkhart et al. 2009; Burkhart et al. 2013). We refer to these works for the details of the numerical set-up and here provide a short overview.

We use the isothermal MHD code detailed in Cho & Lazarian (2003) and vary the input values for the sonic ($M_s = v/c_s$, where v is the flow velocity and c_s is the sound speed) and Alfvénic Mach number ($M_A = v/v_A$, where v_A is the Alfvén speed). The code is a third-order-accurate ENO scheme which solves the ideal MHD equations in a periodic box with purely solenoidally driving. The magnetic field consists of the uniform background field and a turbulent field, i.e: $\mathbf{B} = \mathbf{B}_{ext} + \mathbf{b}$. Initially $\mathbf{b} = 0$.

In total we have 14 simulations at resolution 512^3 . The simulations have sonic Mach numbers ranging from $M_s \approx 0.5 - 10$. There are two different magnetic field values used in this investigation: $M_A \approx 0.7$ (sub-Alfvénic) and $M_A \approx 2.0$ (super-Alfvénic).

3. BISPECTRUM

The bispectrum technique characterizes and searches for nonlinear interactions and departures from Gaussianity, which makes it a useful technique for studies of MHD turbulence in the context of the ISM and solar wind. This is because as turbulence eddies evolve they transfer energy from large scales to small scales generating a hierarchical turbulence cascade as $k_1 + k_2$ interact to

form k_3 . For incompressible flows, under Kolmogorov assumptions, this can be expressed as $k_1 \approx k_2 = k$ and $k_3 \approx 2k$. Nonlinear wave-wave interactions take place more strongly in compressible and magnetized flows and in that case we can have $k_1 \neq k_2$. The utility of the bispectrum or other three-point statistics is that they can characterize nonlinear interactions in both Fourier amplitude and phase (see Barnett 2002; Masahiro & Bhuvnesh 2004).

The bispectrum can be defined as:

$$B(|\vec{k}_1|, |\vec{k}_2|) = \sum_{|\vec{k}_1|=const} \sum_{|\vec{k}_2|=const} A(|\vec{k}_1|) \cdot A(|\vec{k}_2|) \cdot A^*(|\vec{k}_1| + |\vec{k}_2|) \quad (2)$$

where k_1 and k_2 are the wave numbers of two interacting waves, and $A(\vec{k})$ is the original discrete time series data with finite number of elements with $A^*(\vec{k})$ representing the complex conjugate of $A(\vec{k})$. We refer to Burkhart et al. (2009) for more details about the numerical calculation of the bispectrum. The final result of our calculation is a 2D isocontour image of bispectral amplitudes as a function of wave vectors k_1 and k_2 (all angular information in the bispectral triangles is averaged out).

The bispectrum of density and column density was studied in Burkhart et al. (2009) using 2D isocontour plots. Burkhart et al. (2009) found that simulations with higher sonic Mach number and an increased magnetic field produced more mode correlation across a larger range of scales. In particular, Burkhart et al. (2009) found this result applied to both 3D density and observable 2D column density. Due to the bispectrum's sensitivity to the sonic Mach number and magnetic field when applied to column density, Burkhart et al. (2010) performed a follow-up study on the HI column density map of the SMC in order to constrain the nonlinear interaction of turbulence in atomic hydrogen gas. Burkhart et al. (2010) also compared the bispectrum to other statistical methods for obtaining turbulence parameters.

The issues faced in the above mentioned studies concerning the use of the bispectrum of column density maps for finding M_s and M_A is that the 2D isocontour maps of observations are difficult to compare to simulations. In this paper, one of our aims to condense the information provided by the bispectral amplitudes into a more readily understandable 1D form. In order to achieve this, we focus on two different averaging procedures in order to distill the information in the 2D isocontour images of the bispectral amplitudes into a 1D plot. We use both averaging along different annuli for a given $R^2 = k_1^2 + k_2^2$, and angular averaging of all values along a line with given angle α , as measured from the k_1 axis³. Figure 1 shows an example of both averaging procedures on a 2D isocontour map of the bispectrum amplitudes.

Figure 2 shows the averaged bispectral amplitudes of column density with LOS in the X direction with an angular averaging of all values along a line with given angle α . We do not find the averaging procedure is sensitive to the LOS direction and show only the direction parallel

³ Note that it doesn't matter if we average with respect to the k_1 or k_2 axis since the bispectral amplitudes are symmetric about $k_1=k_2$.

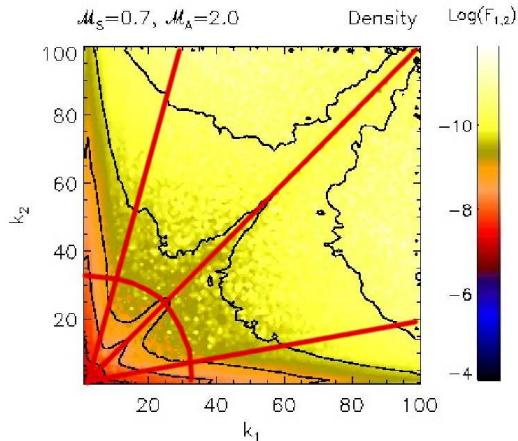


FIG. 1.— Example of the two bispectral averaging procedures used in this paper. Radial averaging averages all bispectral amplitude values for a given $R^2 = k_1^2 + k_2^2$ (example of red circular curve that intersects $k_1 = k_2 = 33$). Angular averaging of the bispectral amplitudes averages all bispectral amplitudes for a given angle (α) as measured from zero (e.g. the three red radial lines shown as an example).

to the mean magnetic field. As expected, past $\alpha = 45$ degrees the averaged values of the isocontours are the same as the bispectrum is symmetric about the $k_1 = k_2$ axis. Furthermore also as expected the highest amplitude occurs at the averaging along $k_1 = k_2$ line, which is equivalent to setting $\alpha = 45$ degrees.

Burkhart et al. (2009) found increased bispectral amplitudes for simulations with higher sonic Mach number, since these simulations depart strongly from Gaussian distributions. Figure 2 reflects this finding in a more compact way. The higher the sonic Mach number, the larger the bispectral amplitudes are and therefore the higher the average is. This is true regardless if the simulations are super-Alfvénic or sub-Alfvénic and we do not see a strong difference between the left and right panels of Figure 2 which show different magnetic field strengths. Thus we can conclude that angular averaging of bispectral isocontour values along a given α is sensitive to the sonic Mach number regardless of the Magnetic field strength.

Figure 3 shows the averaged bispectral amplitudes of column density with LOS in the X direction, respectively, with averaging along different annuli for a given $R^2 = k_1^2 + k_2^2$. Similar to the averaging over different α , averaging the bispectral amplitudes over different annuli shows a strong sensitivity to the sonic Mach number. Column density maps produced from simulations with larger sonic Mach number show higher values of averaged bispectral amplitudes. However, comparing the left and right panels in Figure 3, it is clear that the averaging along different annuli also shows a sensitivity to the magnetic field strength. Simulations with $M_A = 2.0$ show slightly larger averaged amplitudes as compared with simulations with $M_A = 0.7$ for a large range of different sonic Mach numbers. These findings persist regardless of the LOS direction and we do not find that this diagnostic is very sensitive to the LOS with respect to the mean magnetic field orientation, hence we show only the LOS parallel to the mean field direction. Thus we can conclude that averaging the bispectral amplitudes

over different annuli is sensitive to both the sonic and Alfvénic Mach numbers.

It is particularly encouraging that both averaging procedures have slightly different sensitivities to the parameters of the turbulence. The annuli averaging is sensitivity to both sonic and Alfvénic Mach numbers while the angular averaging is sensitive only to sonic Mach number. In both cases, the LOS does not seem to play a significant role in the overall amplitudes. These differences will allow researchers to break the degeneracy in the bispectrum’s sensitivity to multiple turbulence parameters.

4. THE PHASE COHERENCE

4.1. Phase Coherence Technique

The PCI was first introduced in Hada et al. (2003) and Koga & Hada (2003) in order to evaluate the degree of phase coherence among Fourier modes. In essence the technique involves the construction of two surrogate data sets from an original N-dimensional data set. In particular, given an original sequence of data, henceforth denoted as ORG (e.g. time series data or fluctuations of density along a position axis) we can construct two surrogate data sets with the same power spectrum but randomly shuffle the phases for one data set and, for the other surrogate data set, perfectly correlate the phases by setting them equal. We denote the surrogate data with Gaussian random phases as the phase-randomized surrogate (PRS) and the data with correlated phases as the phase-correlated surrogate (PCS). The three data sets, ORG, PRS and PCS, share exactly the same power spectrum, while their phase distributions are all different. Figure 4 shows an example of three different data sets, original plus two surrogate data sets, their identical power spectrum and different phase distributions.

We define the path length similar to that of Koga et al. 2008

$$L(\tau) = \sum_t |x(t + \tau) - x(t)| \quad (3)$$

Where τ is the lag value. In our application of $L(\tau)$, we use spatial increments whereas Koga et al. (2008) used time series data. When the phases of a given data set are correlated the path length will be smaller than in situations where the phases are randomized. Because of this the phase coherence index can be defined as:

$$C_\phi(\tau) = \frac{L_{PRS}(\tau) - L_{ORG}(\tau)}{L_{PRS}(\tau) - L_{PCS}(\tau)} \quad (4)$$

and gives an evaluation on the degree of coherence in the phases. If the original data have randomized phases than C_ϕ should be roughly zero. If C_ϕ is close to unity then this indicates that the phases are nearly completely correlated.

In practice we averaged together five random Gaussian realizations to construct the phases of the PRS data set. Along with the original data (ORG), we use one realization of the PCS (all phases are set to unity). We calculate the first order structure function of the ORG, PRS and PCS data sets (i.e. we apply Equation 3) and then compute the phase coherence given in Equation 4. A schematic of the ORG, PCS and PRS data sets is shown in Figure 4.

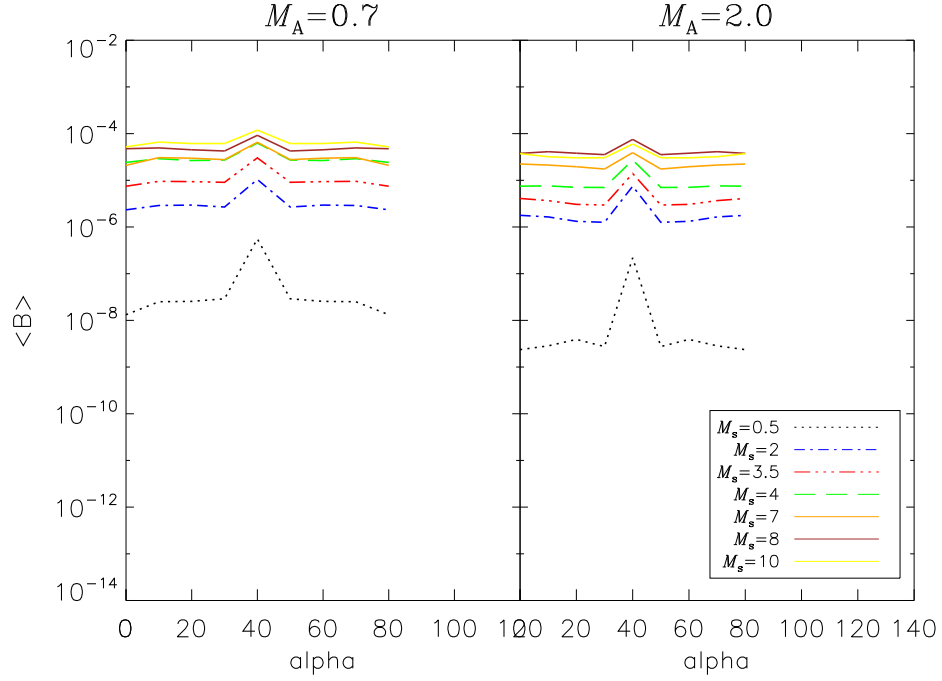


FIG. 2.— Bispectral amplitudes of column density along the magnetic field (X-direction) which are radial averaged along different angles (α).

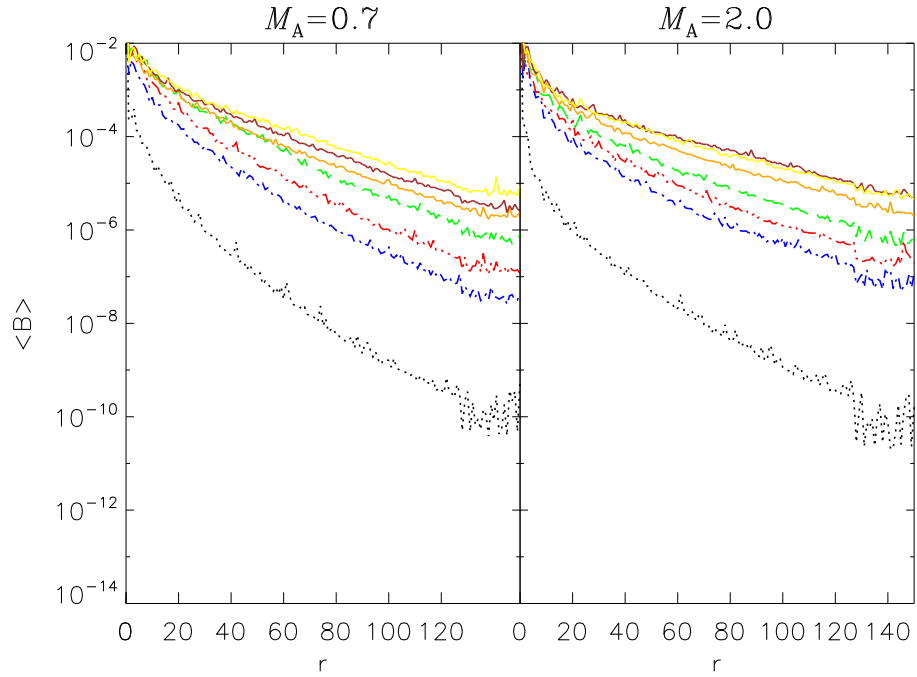


FIG. 3.— Bispectral amplitudes of column density along the magnetic field (X-direction) averaged along different annuli, i.e. for a given $r^2 = k_1^2 + k_2^2$. The left panel shows sub-Alfvénic simulations and the right panel shows super-Alfvénic simulations. The color scheme is the same as in Figure 3.

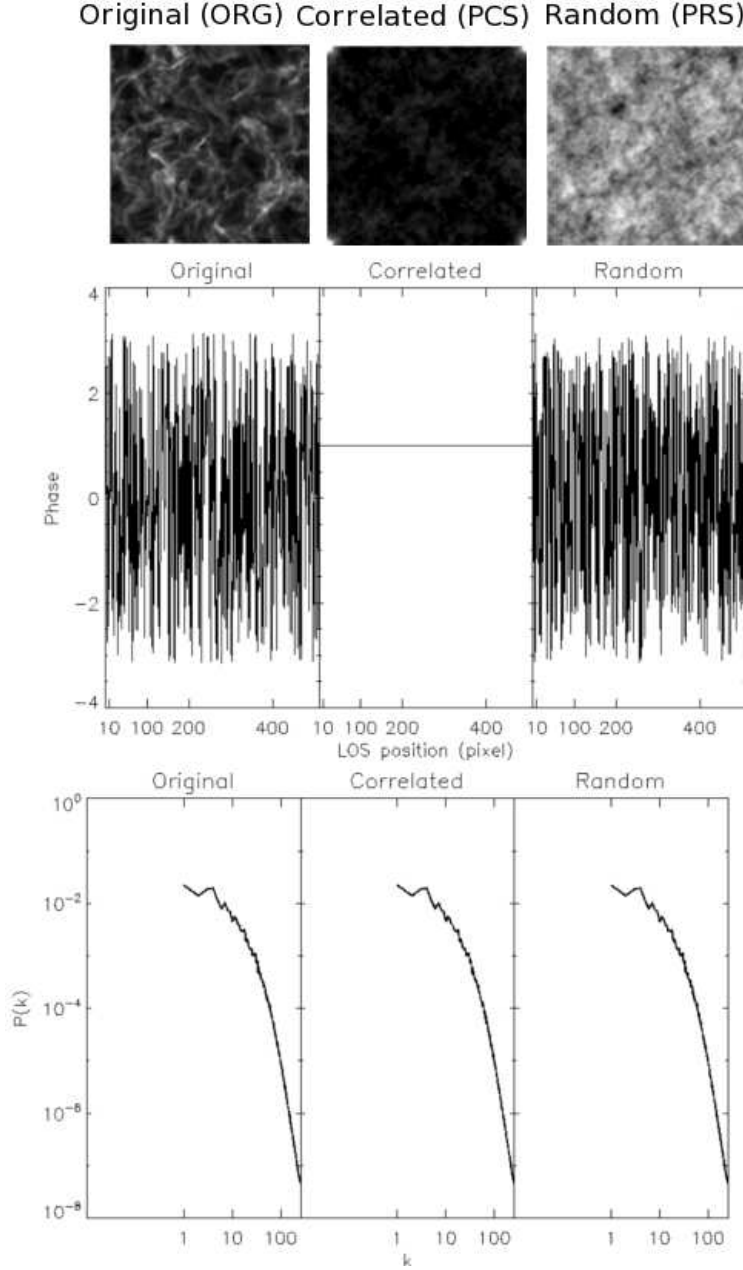


FIG. 4.— The three data sets required for the application of the phase coherence technique. The original data image (ORG) from a supersonic sub-Alfvénic is shown in the top left. From the original data set we construct two surrogate data sets with correlated phase (PCS data, center top image) and with random phases (PRS, top right image). The same positional line of sight cut through the phase is shown for each data set in the central panel. The corresponding power spectrum (shown in the bottom panels) is unchanged and the same for all data sets.

4.2. The Phase Coherence of Density

We plot the phase coherence, $C_\phi(\tau)$ vs. τ , of density in Figure 5. The left panel shows simulations with sub-Alfvénic turbulence while the right panel shows simulations with super-Alfvénic turbulence. Different sonic Mach number runs are denoted with different colors and linestyles.

The phase coherence is peaked at unity for simulations with highly correlated phases and approaches zero when the phases are random. The largest values of the phase coherence occur at the smallest lag values and decrease and eventually saturate at higher lag values. The saturation occurs roughly at lag=40 for all simulated boxes with smaller values than this being well within the dissipation range of our simulations. This indicates that the dissipation region of the simulations show the greatest enhancement of phase coherence. In the inertial range of the simulations the phase coherence is roughly constant across different lag values. This is in contrast to the power spectrum (or the analogous structure function), which decrease as a powerlaw in the inertial range but lacks any phase information.

Like other phase analysis techniques such as the bispectrum, $C_\phi(\tau)$ has a strong dependence on the sonic Mach number of the simulation. Subsonic simulations (shown with black dotted lines) have phase distributions that are closer to random ($C_\phi(\tau) \leq 0.35$). This is not surprising since subsonic turbulence has many statistical features in common with a Gaussian distribution, i.e. low bispectral amplitudes (see Burkhart et al. 2009), similar topological features (see Chepurnov et al. 2008), and a lognormal PDF (see Kowal, Lazarian & Beresnyak 2007). As the sonic Mach number increase the phase coherence also increases. In the inertial range there is nearly no overlap between different MHD runs for different sonic Mach number (for the same M_A), making the phase coherence a sensitive diagnostic of the sonic Mach number.

Comparison between the left and right panel of Figure 5 also shows that, like the bispectrum, the phase coherence is also sensitive to the magnetic field information present in the data. Simulations with a higher mean magnetic field (i.e. sub-Alfvénic simulations) show enhanced values of C_ϕ . This suggests that the phase coherence might also be used to assess the Alfvénic nature of the gas when the sonic Mach number is known.

To demonstrate the above point we average the values of C_ϕ over lag values from 40 to 100 and plot the average C_ϕ vs. sonic Mach number of the simulation in Figure 6. The average phase coherence increases with increasing sonic Mach number and levels off near $C_\phi(\tau) = 1$ for Mach numbers greater than 8. This suggests that the phase coherence will be a sensitive diagnostic of sonic Mach number out to $M_s \approx 8$ however for larger sonic Mach numbers the phase coherence approaches unity. This is similar to the findings of Koga et al. (2008), who found higher phase coherence values at the Earth's bow shock. Additionally, there is a slight degeneracy with the strength of the magnetic field, which becomes even more apparent when averaging the phase coherence. Stronger magnetic field produces density fluctuations which have more correlated phases.

4.3. The Phase Coherence of Column Density

We apply the phase coherence to 2D images of column density maps created from the 3D density distributions in order to test the applicability of the PCI for observations of the ISM. We plot the PCI vs. lag for column density in Figure 7. Similar to our analysis of the bispectrum we test three different LOS orientations but find that the PCI is not particularly sensitive to the LOS orientation and opt to show the figure only for the perpendicular direction along the Z-axis.

The PCI of the column density shows similar overall trends as that of the 3D density. In particular, the PCI is very sensitive to the sonic Mach number of the gas, with more supersonic runs having a higher value of the PCI, suggesting that the phases are more correlated overall. Similarly the dissipation range of the simulation is clearly visible in the overall behavior of the PCI of column density. This suggests that the PCI might be used to determine the dissipation range in observations that resolve it. However there are a number of notable differences of the PCI of column density as compared with 3D density. For example the overall values of the PCI are much lower for column density than they are for density. This is perhaps due to averaging multiple random cells along the LOS to produce the column density maps. Another major difference is that the PCI's sensitivity to the magnetic field intensity is not as apparent in the column density as it is in density maps.

When we plot the average the values of C_ϕ over lag values from 40 to 100 (shown in Figure 8) for column density using all three LOS orientations the lack of sensitivity of the column density PCI to magnetic field and LOS become even more apparent. Nevertheless, the PCI of column density is still sensitive to the overall sonic Mach number of the gas and the dissipation scale, making this technique useful for determining these parameters of ISM turbulence from column density maps.

5. DISCUSSION

Phase information is often ignored in studies of turbulence, which generally focus on the Fourier power spectrum i.e., the Fourier amplitudes. The studies of power spectrum resulted in substantial progress of our understanding of interstellar turbulence. For instance, the Big Power Law in the Sky (Armstrong et al. 1995, Chepurnov & Lazarian 2010), as well as studies of random densities (see Elmegreen & Scalo 2004, for a review) and velocities (see Chepurnov et al. 2015, Lazarian 2009 for a review) provided convincing evidence for the existence and importance of turbulence in the interstellar media.

Nevertheless, power spectra as well as its real space counterparts, namely, structure functions and correlation functions (see Monin & Yaglom 1972) cannot provide the full description of the turbulent field. This induced extensive studies of alternative measures of turbulence. Probability distribution functions of column densities including different measures obtained with them, e.g. skewness and kurtosis (Burkhart et al. 2009, 2010), Tsallis statistics (Esquivel & Lazarian 2010, Toffelmire et al. 2011), dispersions (Burkhart & Lazarian 2012), were considered as tools in order to obtain the properties of turbulence from observations. Together with the techniques for anisotropy of turbulence studies (Lazarian et

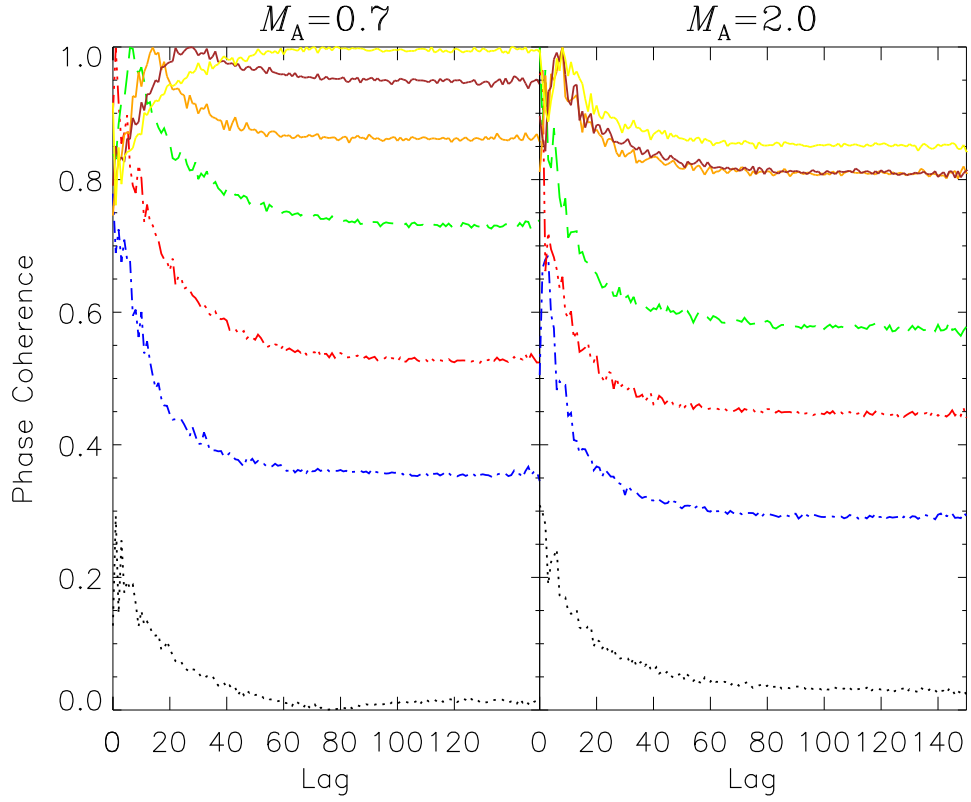


FIG. 5.— The phase coherence $C_\phi(\tau)$ vs. τ of density. The left panel shows simulations with sub-Alfvénic turbulence while the right panel shows simulations with super-Alfvénic turbulence. Different sonic Mach number runs are denoted with different colors and linestyles. The color scheme is the same as in Figure 2.

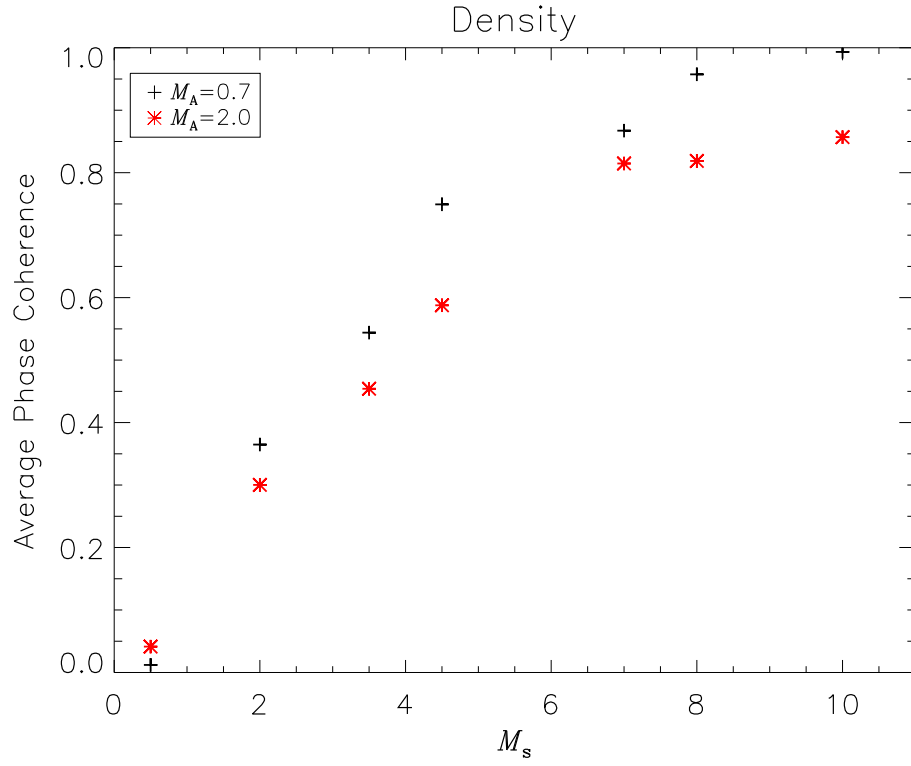


FIG. 6.— Averaged values of C_ϕ vs. the sonic Mach number for 3D density fields. We average values of C_ϕ over lag values from 40 to 100. Super-Alfvénic simulations are denoted with red stars while sub-Alfvénic simulations are denoted with black plus symbols.

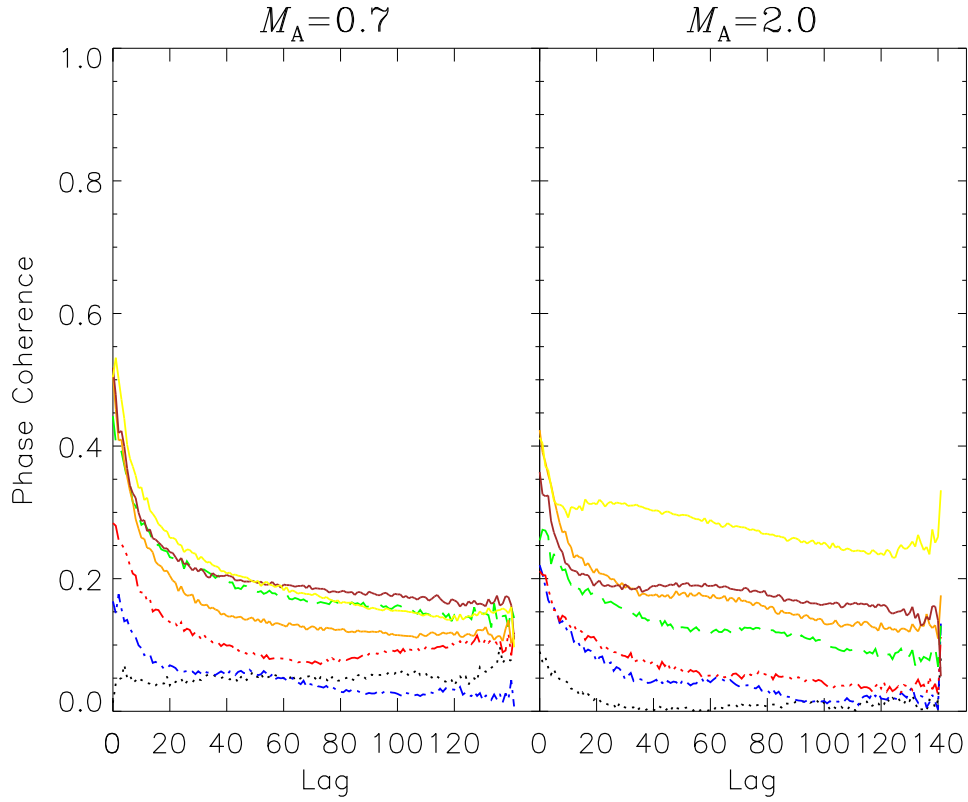


FIG. 7.— Same as Figure 5 but for column density integrated along the Z axis. The left panel shows simulations with sub-Alfvénic turbulence while the right panel shows simulations with super-Alfvénic turbulence. Different sonic Mach number runs are denoted with different colors and line styles. The color scheme is the same as in Figure 2.

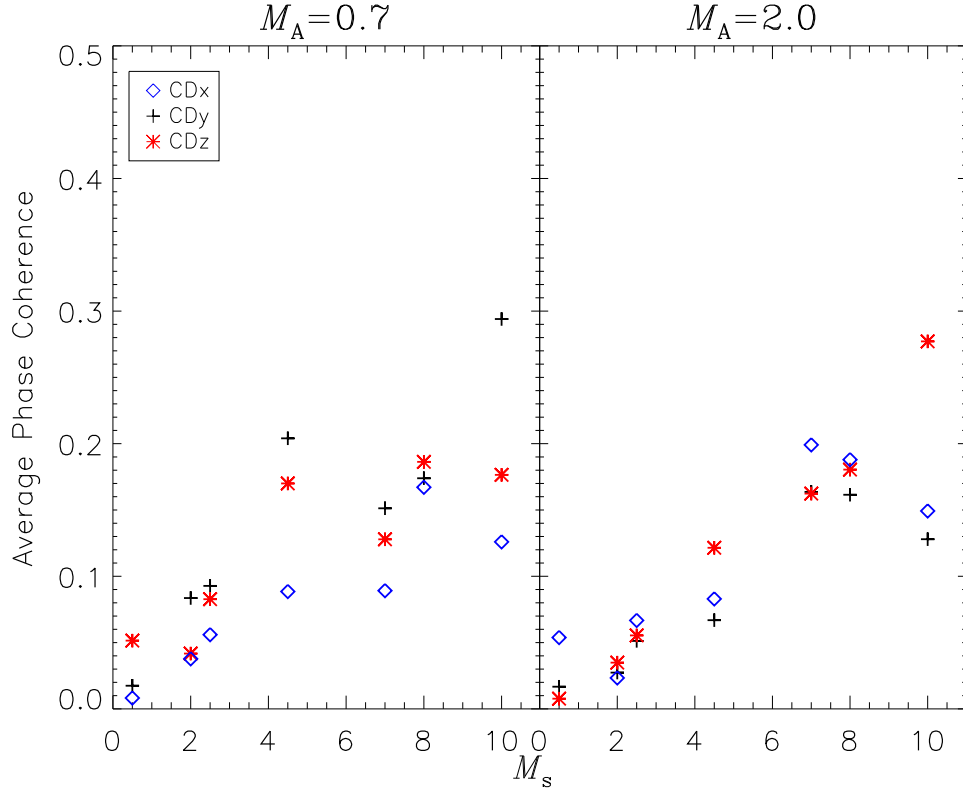


FIG. 8.— Averaged values of C_ϕ vs. the sonic Mach number for 2D column density fields. We average values of C_ϕ over lag values from 40 to 100.

al. 2002, Esquivel & Lazarian 2005, 2011, Heyer et al. 2008, Burkhart et al. 2014) and intermittency studies (Padoan et al. 2004, Kowal et al. 2007) those present an impressive toolbox for quantitative studies of interstellar turbulence.

At the same time, it is known that nonlinear interactions among MHD waves are likely to produce finite correlation of the wave phases and therefore the phases should be studied. Recently several studies have promoted the study of phase information for ISM MHD turbulence. These include three-point statistics, such as the bispectrum studied here as well as in Burkhart et al. (2009, 2010). Furthermore, it was recently shown in Correia et al. (2015) that the principle component analysis (PCA) (see Heyer & Schloerb 1997, Heyer et al. 2008). has sensitivity to the phase information. Intermittency studies also utilize the information of phases.

In spite of the aforementioned studies, this is the first paper, as far as we are aware of, which is entirely focused on making use of the information about phases to provide simple measures that can be used to study interstellar turbulence. For instance, the bispectrum is a rich measure which presents a two dimensional distribution. In this paper we condensed the information provided by the bispectrum by presenting two simple functions, which describe the radial and azimuthally averaged measures of bispectrum. In addition, we presented the measures of the phase coherence index, which can provide another way to characterize the phase information related to turbulence. We find that in shock dominated turbulence the PCI approaches unity, in agreement with solar wind studies such as those of Koga et al. (2008). This is equally true for the bispectrum, where correlation of wave modes increases for supersonic highly magnetized turbulence, as first discussed in Burkhart et al. (2009) for the ISM.

Our present paper continues the trend of bringing the statistical techniques that were developed in other areas into studies of interstellar turbulence. For instance, PCI, similar to Tsallis statistics was first used for the solar wind studies (Burlaga et al 2006, 2007, 2009). With the advent of new telescopes and precision measurements we expect many of the interstellar turbulence techniques to be used for studying turbulence in galaxy clusters. In fact, we believe in cross pollination of different branches

of turbulence research. For instance, we think that our suggestions of bispectrum averaging may be useful for studying turbulence beyond the interstellar turbulence domain and could also be used for cosmological studies, which already employ the bispectrum.

6. CONCLUSIONS

We investigated the utility of two statistical diagnostics for recovering information on Fourier phases in the ISM using a set of simulations of MHD turbulence with a larger range of sonic and Alfvénic Mach numbers. In particular, we focused our study on a new averaging procedure for the bispectrum isocontour amplitudes in order to distill the information in the isocontours into a 1D form. We also introduce the phase coherence index, a new technique for studies of density fluctuations in the ISM.

We find that:

- The bispectrum averaged along different angles with respect to either the k_1 or k_2 axis is primarily sensitive to the sonic Mach number.
- Averaging the bispectral amplitudes over different annuli is sensitive to both the sonic and Alfvénic Mach numbers.
- Higher sonic Mach number and larger magnetic field produce density structures which have more correlated phases behavior compared to a random Gaussian distribution of phases.
- We find that in shock dominated turbulence the PCI approaches unity, in agreement with solar wind studies.
- The PCI of density is sensitive to both the sonic and Alfvénic Mach numbers. However when applied to column density maps the PCI is sensitive only to the sonic Mach number.

The research of B.B. is supported by the NASA Einstein Postdoctoral Fellowship.

REFERENCES

- Armstrong, J. W., Rickett, B. J., & Spangler, S. R. 1995, *ApJ*, 443, 209
- Barnett, A. G. 2002, PhD Thesis, School of Physical Sciences, The Univ. of Queensland
- Burkhart, B., & Lazarian, A. 2012, *ApJ*, 755, L19
- Burkhart, B., Lazarian, A., Leão, I. C., de Medeiros, J. R., & Esquivel, A. 2014, *ApJ*, 790, 130
- Burkhart, B., et al., 2009, *ApJ*, 693, 250
- Burkhart, B., et al., 2010, *ApJ*, 708, 1204
- Burkhart, B., et al., 2013a, *ApJ*, 771, 122
- Burlaga, L. F., Ness, N. F., & Acuña, M. H., 2009, *ApJ*, 691, L82
- Burlaga, L. F., Ness, N. F., & Acuña, M. H., 2007, *APT*, 668, 1246
- Burlaga, L. F., Ness, N. F., & Acuña, M. H., 2006, *ApJ*, 642, 584
- Chian, A. C., et al., 2008, *Non.Proc.Geophys*, 15, 567
- Chian, A. C., et al., 2010, *PhRvL*, vol. 104, Issue 25
- Chepurnov, A., Gordon, J., Lazarian, A., Stanimirovic, S., 2008, *ApJ*, 688, 1021
- Chepurnov, A., & Lazarian, A. 2010, *ApJ*, 710, 853
- Chepurnov, A., Burkhart, B., Lazarian, A., & Stanimirovic, S., 2015, *ApJ*, 810, 33
- Cho, J., Lazarian, A., & Vishniac, E. T. 2002, *ApJ*, 564, 291
- Cho, J., & Lazarian, A. 2003, *MNRAS*, 345, 325
- Cho, J., & Lazarian, A., 2009, *ApJ*, 701, 236
- Collins, D., et al., 2012, *ApJ*, 750, 13
- Correia, C., et al. (2015), *ApJ*, submitted.
- Elmegreen, B. G., & Scalo, J. 2004, *ARA&A*, 42, 211
- Esquivel, A., & Lazarian, A. 2005, *ApJ*, 631, 320
- Esquivel, A., & Lazarian, A. 2005, *ApJ*, 631, 320
- Esquivel, A., & Lazarian, A. 2010, *ApJ*, 710, 125
- Esquivel, A., & Lazarian, A. 2011, *ApJ*, 740, 117
- Federrath, C., & Klessen, R., 2013, *ApJ*, 763, 51
- Hada T, Koga D, Yamamoto, E., 2003, *Space Sci. Rev.* 107, 463
- Heyer, M., Gong, H., Ostriker, E., & Brunt, C. 2008, *ApJ*, 680, 420
- Heyer, M. H., & Peter Schloerb, F. 1997, *ApJ*, 475, 173
- Koga D, Hada ,T., 2003, *Space Sci. Rev.* 107, 495
- Koga, D., et al. 2007, *Phys. Rev.*, 75, 046401
- Koga, D., et al., 2008, *RSTA*, 366, 1864
- Kowal, G., Lazarian, A., & Beresnyak, A. 2007, *ApJ*, 658, 423
- Lazarian, A., 2009, *SSRv*, 143, 357

- Lazarian, A., Pogosyan, D., & Esquivel, A. 2002, Seeing Through the Dust: The Detection of HI and the Exploration of the ISM in Galaxies, 276, 182
- Masahiro, T., & Bhuvnesh, J. 2004, MNRAS, 348, 897
- Ossenkopf, V. 2002, A&A, 391, 295
- Padoan, P., Jimenez, R., Nordlund, Å., & Boldyrev, S. 2004, Physical Review Letters, 92, 191102
- Tofflemire, B. M., Burkhart, B., & Lazarian, A. 2011, ApJ, 736, 60